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Greenland ice sheet melt from MODIS and associated atmospheric variability

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Key Points:
- Short-term atmospheric blocking over Greenland contributes to melt episodes
- Associated temperature anomalies are equally important for the melt
- Duration and strength of blocking events contribute to surface melt intensity

Supporting Information:
- Readme
- Text S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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Abstract Daily June-July melt fraction variations over the Greenland ice sheet (GIS) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) (2000–2013) are associated with atmospheric blocking forming an omega-shape ridge over the GIS at 500 hPa height. Blocking activity with a range of time scales, from synoptic waves breaking poleward (<5 days) to full-fledged blocks (≥5 days), brings warm subtropical air masses over the GIS controlling daily surface temperatures and melt. The temperature anomaly of these subtropical air mass intrusions is also important for melting. Based on the years with the greatest melt (2002 and 2012) during the MODIS era, the area-average temperature anomaly of 2 standard deviations above the 14 year June-July mean results in a melt fraction of 40% or more. Though the summer of 2007 had the most blocking days, atmospheric temperature anomalies were too small to instigate extreme melting.

1. Background

Recently, a data record of the clear-sky ice surface temperature (IST) of the Greenland ice sheet (GIS) was developed using Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Terra and Aqua satellites [*Hall et al.*, 2012]. The record extends from March 2000 through the present, providing daily and monthly average IST, and melt maps at 6.25 × 6.25 km resolution. Based on this MODIS IST record, years experiencing major melt (defined as melt covering 80% or more of the ice sheet surface) have occurred twice since 2000 [*Hall et al.*, 2013]. The extreme melt year of 2012 had two separate intense melt events. The most unusual melt event occurred on 11–12 July 2012 and was unprecedented during this and the previous century, covering ~99% of the ice sheet surface including areas >3000 m at Summit Station (Figure 1a) according to data from multiple satellite sensors [*Nghiem et al.*, 2012]. Melt this extensive had not occurred since 1889 (+/− 1 year) according to ice core records [*Nghiem et al.*, 2012; *Clausen et al.*, 1988; *Alley and Anandakrishnan*, 1995]. Another large melt event occurred on 29 July 2012, where ~79% of the surface experienced some melt according to data from multiple satellite sensors [*Nghiem et al.*, 2012]. In 2002 an intense melt event occurred on 29 June to 2 July. The cumulative melt during the 2002 melt season covered > 87% of the ice sheet surface according to MODIS IST clear-sky data [*Hall et al.*, 2013].

The negative phase of the North Atlantic Oscillation (NAO), with a high-pressure anomaly over the GIS, has previously been implicated [*Mote*, 1998] in enhancing melting of the surface of the GIS. Also, the 2012 melt event was associated with a high-pressure ridge over the GIS [*Nghiem et al.*, 2012; *Tedesco et al.*, 2013; *Hanna et al.*, 2013]. A high-pressure ridge brings relatively warm southerly winds over the western flank of the ice sheet causing widespread surface melting [*Nghiem et al.*, 2012]. A high-pressure ridge also represents atmospheric blocking, which is a long-lived (5 days or longer) atmospheric circulation system with strong meridional flows embedded within the latitude belt of westerlies [*Tibaldi and Molteni*, 1990; *Tibaldi et al.*, 1997] (definition also shown in the supporting information). Blocking in the North Atlantic sector is usually associated with the negative phase of the NAO, and known as a Greenland Blocking Episode (GBE) [*Fang*, 2004; *Woollings et al.*, 2008]. GBEs have a continuum of behavior, from being relatively frequent but weak events, to longer and stronger events that better conform to the conventional interpretation (and definition) of midlatitude blocking. Here we are also interested in shorter than 5 day blocking activity, because we anticipate that even a 2 day burst of warm subtropical air over the GIS could lead to melting. These short events are called local and instantaneous blocking (LIB), if on any day a longitude is blocked based on the

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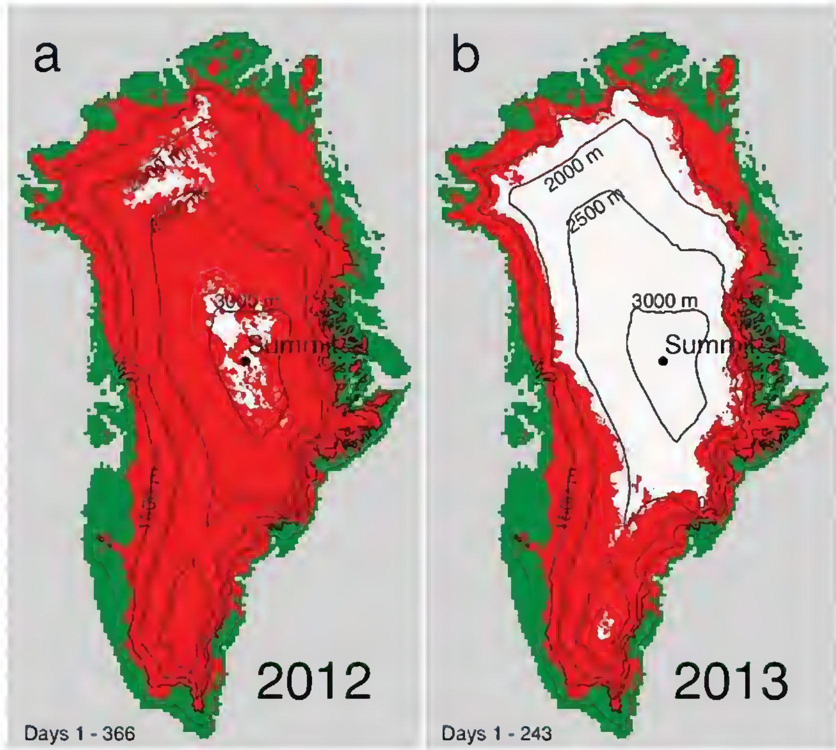

Figure 1. Extent of melt on the Greenland ice sheet for (a) 1 January to 31 December 2012 (days 1–366) and (b) 1 January to 30 August 2013 (days 1–243) as determined from MODIS-derived melt maps. A maximum of ~95% of the ice sheet surface (shaded red) experienced some melt in 2012 and only ~49% of the ice sheet surface experienced some melt in 2013. White represents no melting (according to MODIS), and green represent non-ice covered land areas. The location of Summit, mentioned in the text, is shown. Elevation contours are shown at 1500, 2000, 2500, and 3000 m.

reversal of the gradient in the 500 hPa geopotential height field [*Tibaldi and Molteni*, 1990; *Tyrlis and Hoskins*, 2008]. Some of the LIBs belong to GBEs if they are spatially stationary for 5 days or more.

We focus here on daily variability of melt and atmospheric conditions instead of seasonal variability. Both LIBs and GBEs are accompanied by warm air temperatures and we will show that are both capable of initiating ice sheet melt. We will also show that daily air temperature at about 5 km height, about 2 km above the ice sheet, varies in-phase with MODIS IST in June and July, the months most likely to have intense melt events. Finally, we will discuss the relationship between GIS melt and blocking and associated temperature variability.

2. Data and Methods

We use the MODIS clear-sky IST data record (2000–2013) to calculate GIS melt. For the retrieval of MODIS clear-sky IST, a split-window technique is used, where "split-window" refers to the brightness-temperature difference in the 11–12 m atmospheric window. This technique allows for the correction of atmospheric effects primarily due to water vapor. The technique was first used to determine IST in the Arctic with advanced very high resolution radiometer (AVHRR) data on NOAA polar-orbiting satellites [*Key and Haefliger*, 1992] and later adapted for use with MODIS.

Using MODIS IST we quantify number of melt days and areal extent of melt for each year of the study (Figure 1). Melt that may occur beneath cloud cover will not be detected using this method. Cloud cover is determined from the standard MODIS cloud mask of *Ackerman et al.* [1998]. To partly compensate for the effects of cloud cover, for this work we employ a cloud-gap filling algorithm (see supporting information) to minimize the impact of cloud cover. As in previous work [*Hall et al.*, 2012, 2013], we also classify an IST grid cell as "melt" if the surface temperature is ≥ -1°C. This temperature has been found to be representative of melting conditions over the GIS, in consideration of MODIS IST measurement uncertainty of +/−1°C at the

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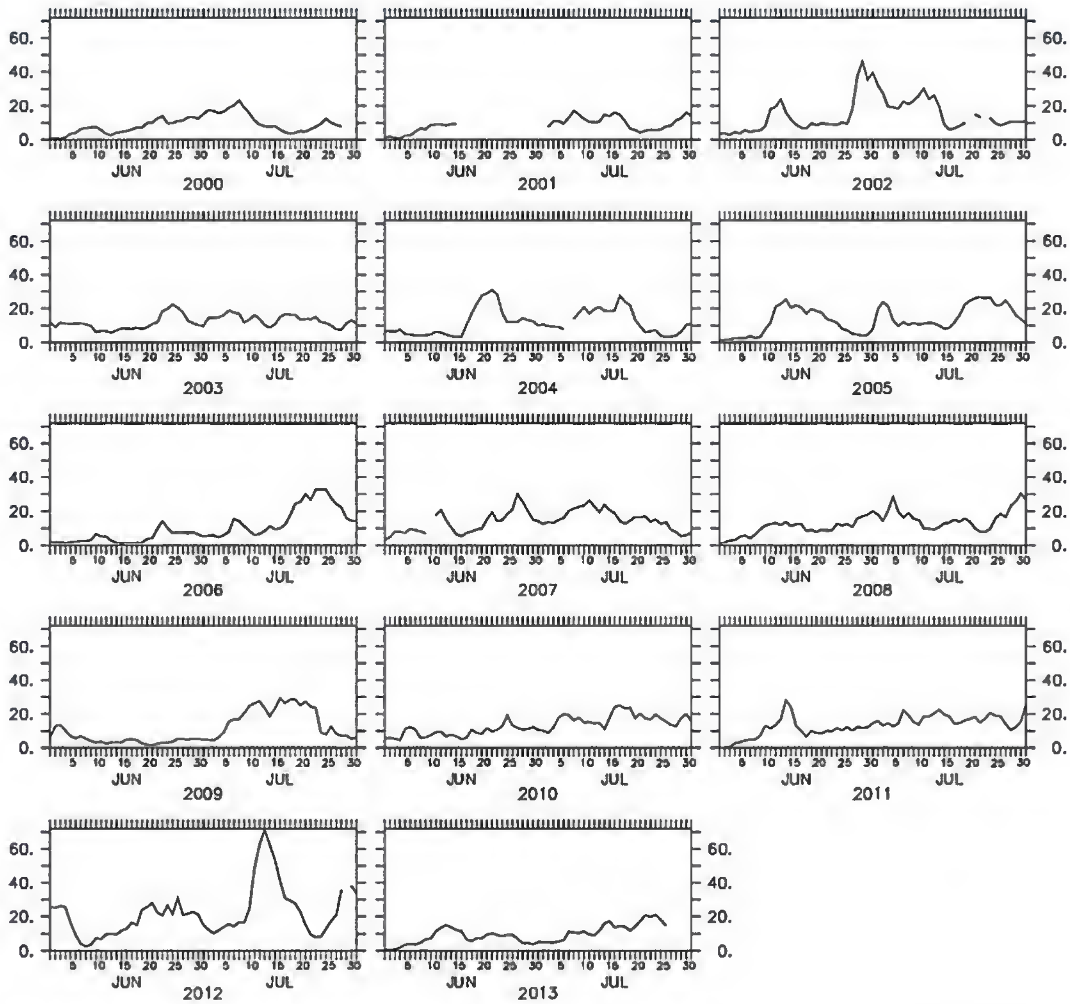

Figure 2. Total melt area percentage over the area of the Greenland ice sheet (*y* axis, %) for June and July for each year, 2000–2013, derived from daily MODIS IST data.

high (near 0°C) values of IST over ice [*Hall et al.*, 2008]. We use daily melt to infer associated atmospheric conditions on a daily basis.

We utilize the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data [*Kalnay et al.*, 1996] to analyze daily average 500 hPa geopotential height (Z500) and temperature (T500), and daily average air temperature at 2 m (T2m), all of which are derived from 6-hourly data. The reanalysis data resolution is 2.5° × 2.5°. To compute area-average temperatures, T500 and T2m were interpolated to the MODIS IST grid of 6.25 km and constrained by the MODIS ice sheet mask. Blocking is computed by searching reversals of the gradient in the daily (average) 500 hPa geopotential height at each grid longitude and latitude in a region 20°W–60°W, 50°N–85°N instead of over fixed latitudes [*Tibaldi and Molteni*, 1990] (supporting information). We record both LIBs and GBEs. Additionally, the NAO indices are retrieved from the NOAA/Climate Prediction Center.

3. Results

The maximum area that experienced at least 1 day of melt during the melt period in 2012 and 2013 is shown in Figures 1a and 1b, as determined from the MODIS IST product. The contrast in the extent of melt between 2012 and 2013 is striking, with MODIS-derived melt covering ~95% of the ice sheet surface in 2012 and ~49% in 2013. (By combining MODIS with microwave sensors that can detect melt through cloud cover, the 2012 melt extent actually covered 99% of the ice sheet surface [*Nghiem et al.*, 2012] as discussed

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Table 1. NAO Index Versus the Total GIS Melt Percentage From MODIS[a]

Year	Melt (%)	June NAO Index	July NAO Index
2000	*54*	*neutral*	*negative*
2001	*51*	*weak negative*	*weak negative*
2002	87	positive	positive
2003	*54*	*~neutral*	*~neutral*
2004	71	negative	positive
2005	62	neutral	negative
2006	62	positive	positive
2007	58	negative	negative
2008	*53*	*negative*	*negative*
2009	63	negative	strong negative
2010	*57*	*negative*	*negative*
2011	64	negative	negative
2012	95	strong negative	negative
2013 (days 1–243)	*49*	*positive*	*positive*

[a]MODIS data updated from *Hall et al.* [2013]; NAO index from NOAA/Climate Prediction Center. Minimal melt years are in italics.

previously.) Using available atmospheric NCEP/NCAR reanalysis fields, we can illuminate the differences in the synoptic regime between these two consecutive years and illustrate the relationship between atmospheric patterns and melt over the entire 2000–2013 melt season MODIS IST record on the daily time scale.

The MODIS-derived daily melt area is shown in Figure 2 for June and July. MODIS melt data are not plotted if the gap-filled cloudiness is >11% of the ice sheet area. (This cutoff of 11% was determined by visual scanning of the cloudiness data and thus appeared to be a logical cutoff value. Though it is a subjective choice, the results do not change significantly if we select a cutoff number between 10 and 15%.) Daily percent melt fractions do not reach as high as quoted above for the cumulative area of melt because the melt location varies day-to-day. The 14 year June-July mean daily melt percentage is 13% and the standard deviation (SD) is 8% (based on 834 daily values excluding MODIS data gaps). The maximum 1 day percent melt of 71% (clear-sky) occurred on 13 July 2012. The only other days with melt percentage over 40% occurred on 29 June 2002 (46%), and 11–12 July (49% and 62%), and 14–16 July (63%, 54%, and 41%) 2012. Low melt years in the MODIS record are the following: 2000 (potentially 2001; based on atmospheric temperatures, shown later), 2003, 2008, 2010, and 2013. In each of the low melt years, the average June-July melt fraction was less than or equal to the 14 year June-July mean. The low melt years 2000 (2001), 2003, 2008, and 2010 occurred during a negative or neutral NAO phase (Table 1 and the NAO index in Figure S1 in the supporting information), which should have favored increased melt. The low melt in 2013, however, was associated with a positive NAO index as expected. Another example of NAO with a "wrong sign" is the extensive melt year 2002, which was dominated by a positive phase of the NAO (Table 1). Thus, the GIS melt-NAO relationship is not consistent during the MODIS years, and when using daily NAO index data, the NAO index explains only 15% of the GIS melt variance.

To identify the atmospheric pattern associated with the intense melt events in the MODIS record on a daily time scale, we analyzed daily June-July Z500 and T500 fields for 2000–2013. We composited these fields based on the daily anomaly in the MODIS melting fraction as an index time series. The daily MODIS melt anomalies were derived, and the MODIS melt index was formed, by normalizing the anomaly time series by its SD:

$$\text{Melt index} = |(\text{daily melt}) - (\text{mean\_daily\_melt})|/\text{SD}, \text{where mean\_daily\_melt} = 13\%; \text{ and SD} = 8\%$$

We selected Z500 and T500 fields from the days when the melt index exceeded 1 SD (in absolute terms). This approach groups the selected Z500 and T500 fields to positive melt index anomaly days (120 fields) and negative melt index anomaly days (113 fields). The composited fields show that the large melt events are associated with a meander in the Z500 field resembling an Omega-block (□ pattern, see Figures 3a and 3b) over Greenland, with lows flanking the high-pressure domain. Minimal melt anomalies are associated with a more-or-less zonal flow over the ice sheet (Figures 3c and 3d). The warmest intrusion of the subtropical air masses envelopes both western and eastern flanks of the GIS south of about 75°N. However, the influence of

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